

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

*Application
for
United States Letters Patent*

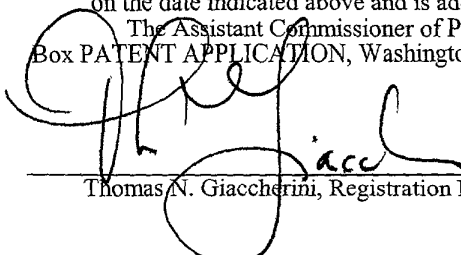
Body Motion Tracking System

CERTIFICATE OF MAILING BY U.S.P.S. EXPRESS MAIL

Mailing Label Number
EL 776 133 139 US

Date of Deposit
26 January 2001

The undersigned hereby certifies that
this document is being deposited
with the United States Postal Service
"Express Mail Post Office to Addressee Service"
in accordance with the provisions of 37 CFR Section 1.10
on the date indicated above and is addressed to
The Assistant Commissioner of Patents,
Box PATENT APPLICATION, Washington, D.C. 20231.


Thomas N. Giaccherini, Registration No. 31,075

26 January
2001.

Inventors:
Ronald J. Kane
David Stevenson Spain, Jr.

Body Motion Tracking System

INTRODUCTION

The title of the Invention is *Body Motion Tracking System*. The Inventors are Ronald J. Kane of 3679 Canelli Ct., Pleasanton, California 94566; and David Stevenson Spain, Jr. of 4760 Alpine Road, Portola Valley, California 94028. Both Inventors are citizens of the United States of America.

FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

None.

FIELD OF THE INVENTION

The present invention relates to the field of motion analysis. More particularly, the invention pertains to clinical research and health care for persons with disabilities, athletes and athletic coaches, and the sports and entertainment industries.

TER-2000-1

BACKGROUND OF THE INVENTION

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100 101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116 117 118 119 120 121 122 123 124 125 126 127 128 129 130 131 132 133 134 135 136 137 138 139 140 141 142 143 144 145 146 147 148 149 150 151 152 153 154 155 156 157 158 159 160 161 162 163 164 165 166 167 168 169 170 171 172 173 174 175 176 177 178 179 180 181 182 183 184 185 186 187 188 189 190 191 192 193 194 195 196 197 198 199 200 201 202 203 204 205 206 207 208 209 210 211 212 213 214 215 216 217 218 219 220 221 222 223 224 225 226 227 228 229 230 231 232 233 234 235 236 237 238 239 240 241 242 243 244 245 246 247 248 249 250 251 252 253 254 255 256 257 258 259 260 261 262 263 264 265 266 267 268 269 270 271 272 273 274 275 276 277 278 279 280 281 282 283 284 285 286 287 288 289 290 291 292 293 294 295 296 297 298 299 300 301 302 303 304 305 306 307 308 309 310 311 312 313 314 315 316 317 318 319 320 321 322 323 324 325 326 327 328 329 330 331 332 333 334 335 336 337 338 339 340 341 342 343 344 345 346 347 348 349 350 351 352 353 354 355 356 357 358 359 360 361 362 363 364 365 366 367 368 369 370 371 372 373 374 375 376 377 378 379 380 381 382 383 384 385 386 387 388 389 390 391 392 393 394 395 396 397 398 399 400 401 402 403 404 405 406 407 408 409 410 411 412 413 414 415 416 417 418 419 420 421 422 423 424 425 426 427 428 429 430 431 432 433 434 435 436 437 438 439 440 441 442 443 444 445 446 447 448 449 450 451 452 453 454 455 456 457 458 459 460 461 462 463 464 465 466 467 468 469 470 471 472 473 474 475 476 477 478 479 480 481 482 483 484 485 486 487 488 489 490 491 492 493 494 495 496 497 498 499 500 501 502 503 504 505 506 507 508 509 510 511 512 513 514 515 516 517 518 519 520 521 522 523 524 525 526 527 528 529 530 531 532 533 534 535 536 537 538 539 540 541 542 543 544 545 546 547 548 549 550 551 552 553 554 555 556 557 558 559 560 561 562 563 564 565 566 567 568 569 570 571 572 573 574 575 576 577 578 579 580 581 582 583 584 585 586 587 588 589 590 591 592 593 594 595 596 597 598 599 600 601 602 603 604 605 606 607 608 609 610 611 612 613 614 615 616 617 618 619 620 621 622 623 624 625 626 627 628 629 630 631 632 633 634 635 636 637 638 639 640 641 642 643 644 645 646 647 648 649 650 651 652 653 654 655 656 657 658 659 660 661 662 663 664 665 666 667 668 669 670 671 672 673 674 675 676 677 678 679 680 681 682 683 684 685 686 687 688 689 690 691 692 693 694 695 696 697 698 699 700 701 702 703 704 705 706 707 708 709 710 711 712 713 714 715 716 717 718 719 720 721 722 723 724 725 726 727 728 729 730 731 732 733 734 735 736 737 738 739 740 741 742 743 744 745 746 747 748 749 750 751 752 753 754 755 756 757 758 759 760 761 762 763 764 765 766 767 768 769 770 771 772 773 774 775 776 777 778 779 780 781 782 783 784 785 786 787 788 789 790 791 792 793 794 795 796 797 798 799 800 801 802 803 804 805 806 807 808 809 810 811 812 813 814 815 816 817 818 819 820 821 822 823 824 825 826 827 828 829 830 831 832 833 834 835 836 837 838 839 840 841 842 843 844 845 846 847 848 849 850 851 852 853 854 855 856 857 858 859 860 861 862 863 864 865 866 867 868 869 870 871 872 873 874 875 876 877 878 879 880 881 882 883 884 885 886 887 888 889 890 891 892 893 894 895 896 897 898 899 900 901 902 903 904 905 906 907 908 909 910 911 912 913 914 915 916 917 918 919 920 921 922 923 924 925 926 927 928 929 930 931 932 933 934 935 936 937 938 939 940 941 942 943 944 945 946 947 948 949 950 951 952 953 954 955 956 957 958 959 960 961 962 963 964 965 966 967 968 969 970 971 972 973 974 975 976 977 978 979 980 981 982 983 984 985 986 987 988 989 990 991 992 993 994 995 996 997 998 999 1000 1001 1002 1003 1004 1005 1006 1007 1008 1009 1010 1011 1012 1013 1014 1015 1016 1017 1018 1019 1020 1021 1022 1023 1024 1025 1026 1027 1028 1029 1030 1031 1032 1033 1034 1035 1036 1037 1038 1039 1040 1041 1042 1043 1044 1045 1046 1047 1048 1049 1050 1051 1052 1053 1054 1055 1056 1057 1058 1059 1060 1061 1062 1063 1064 1065 1066 1067 1068 1069 1070 1071 1072 1073 1074 1075 1076 1077 1078 1079 1080 1081 1082 1083 1084 1085 1086 1087 1088 1089 1090 1091 1092 1093 1094 1095 1096 1097 1098 1099 1100 1101 1102 1103 1104 1105 1106 1107 1108 1109 1110 1111 1112 1113 1114 1115 1116 1117 1118 1119 1120 1121 1122 1123 1124 1125 1126 1127 1128 1129 1130 1131 1132 1133 1134 1135 1136 1137 1138 1139 1140 1141 1142 1143 1144 1145 1146 1147 1148 1149 1150 1151 1152 1153 1154 1155 1156 1157 1158 1159 1160 1161 1162 1163 1164 1165 1166 1167 1168 1169 1170 1171 1172 1173 1174 1175 1176 1177 1178 1179 1180 1181 1182 1183 1184 1185 1186 1187 1188 1189 1190 1191 1192 1193 1194 1195 1196 1197 1198 1199 1200 1201 1202 1203 1204 1205 1206 1207 1208 1209 1210 1211 1212 1213 1214 1215 1216 1217 1218 1219 1220 1221 1222 1223 1224 1225 1226 1227 1228 1229 1230 1231 1232 1233 1234 1235 1236 1237 1238 1239 1240 1241 1242 1243 1244 1245 1246 1247 1248 1249 1250 1251 1252 1253 1254 1255 1256 1257 1258 1259 1260 1261 1262 1263 1264 1265 1266 1267 1268 1269 1270 1271 1272 1273 1274 1275 1276 1277 1278 1279 1280 1281 1282 1283 1284 1285 1286 1287 1288 1289 1290 1291 1292 1293 1294 1295 1296 1297 1298 1299 1300 1301 1302 1303 1304 1305 1306 1307 1308 1309 1310 1311 1312 1313 1314 1315 1316 1317 1318 1319 1320 1321 1322 1323 1324 1325 1326 1327 1328 1329 1330 1331 1332 1333 1334 1335 1336 1337 1338 1339 1340 1341 1342 1343 1344 1345 1346 1347 1348 1349 1350 1351 1352 1353 1354 1355 1356 1357 1358 1359 1360 1361 1362 1363 1364 1365 1366 1367 1368 1369 1370 1371 1372 1373 1374 1375 1376 1377 1378 1379 1380 1381 1382 1383 1384 1385 1386 1387 1388 1389 1390 1391 1392 1393 1394 1395 1396 1397 1398 1399 1400 1401 1402 1403 1404 1405 1406 1407 1408 1409 1410 1411 1412 1413 1414 1415 1416 1417 1418 1419 1420 1421 1422 1423 1424 1425 1426 1427 1428 1429 1430 1431 1432 1433 1434 1435 1436 1437 1438 1439 1440 1441 1442 1443 1444 1445 1446 1447 1448 1449 1450 1451 1452 1453 1454 1455 1456 1457 1458 1459 1460 1461 1462 1463 1464 1465 1466 1467 1468 1469 1470 1471 1472 1473 1474 1475 1476 1477 1478 1479 1480 1481 1482 1483 1484 1485 1486 1487 1488 1489 1490 1491 1492 1493 1494 1495 1496 1497 1498 1499 1500 1501 1502 1503 1504 1505 1506 1507 1508 1509 1510 1511 1512 1513 1514 1515 1516 1517 1518 1519 1520 1521 1522 1523 1524 1525 1526 1527 1528 1529 1530 1531 1532 1533 1534 1535 1536 1537 1538 1539 1540 1541 1542 1543 1544 1545 1546 1547 1548 1549 1550 1551 1552 1553 1554 1555 1556 1557 1558 1559 1560 1561 1562 1563 1564 1565 1566 1567 1568 1569 1570 1571 1572 1573 1574 1575 1576 1577 1578 1579 1580 1581 1582 1583 1584 1585 1586 1587 1588 1589 1590 1591 1592 1593 1594 1595 1596 1597 1598 1599 1600 1601 1602 1603 1604 1605 1606 1607 1608 1609 1610 1611 1612 1613 1614 1615 1616 1617 1618 1619 1620 1621 1622 1623 1624 1625 1626 1627 1628 1629 1630 1631 1632 1633 1634 1635 1636 1637 1638 1639 1640 1641 1642 1643 1644 1645 1646 1647 1648 1649 1650 1651 1652 1653 1654 1655 1656 1657 1658 1659 1660 1661 1662 1663 1664 1665 1666 1667 1668 1669 1670 1671 1672 1673 1674 1675 1676 1677 1678 1679 1680 1681 1682 1683 1684 1685 1686 1687 1688 1689 1690 1691 1692 1693 1694 1695 1696 1697 1698 1699 1700 1701 1702 1703 1704 1705 1706 1707 1708 1709 1710 1711 1712 1713 1714 1715 1716 1717 1718 1719 1720 1721 1722 1723 1724 1725 1726 1727 1728 1729 1730 1731 1732 1733 1734 1735 1736 1737 1738 1739 1740 1741 1742 1743 1744 1745 1746 1747 1748 1749 1750 1751 1752 1753 1754 1755 1756 1757 1758 1759 1760 1761 1762 1763 1764 1765 1766 1767 1768 1769 1770 1771 1772 1773 1774 1775 1776 1777 1778 1779 1780 1781 1782 1783 1784 1785 1786 1787 1788 1789 1790 1791 1792 1793 1794 1795 1796 1797 1798 1799 1800 1801 1802 1803 1804 1805 1806 1807 1808 1809 1810 1811 1812 1813 1814 1815 1816 1817 1818 1819 1820 1821 1822 1823 1824 1825 1826 1827 1828 1829 1830 1831 1832 1833 1834 1835 1836 1837 1838 1839 1840 1841 1842 1843 1844 1845 1846 1847 1848 1849 1850 1851 1852 1853 1854 1855 1856 1857 1858 1859 1860 1861 1862 1863 1864 1865 1866 1867 1868 1869 1870 1871 1872 1873 1874 1875 1876 1877 1878 1879 1880 1881 1882 1883 1884 1885 1886 1887 1888 1889 1890 1891 1892 1893 1894 1895 1896 1897 1898 1899 1900 1901 1902 1903 1904 1905 1906 1907 1908 1909 1910 1911 1912 1913 1914 1915 1916 1917 1918 1919 1920 1921 1922 1923 1924 1925 1926 1927 1928 1929 1930 1931 1932 1933 1934 1935 1936 1937 1938 1939 1940 1941 1942 1943 1944 1945 1946 1947 1948 1949 1950 1951 1952 1953 1954 1955 1956 1957 1958 1959 1960 1961 1962 1963 1964 1965 1966 1967 1968 1969 1970 1971 1972 1973 1974 1975 1976 1977 1978 1979 1980 1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035 2036 2037 2038 2039 2040 2041 2042 2043 2044 2045 2046 2047 2048 2049 2050 2051 2052 2053 2054 2055 2056 2057 2058 2059 2060 2061 2062 2063 2064 2065 2066 2067 2068 2069 2070 2071 2072 2073 2074 2075 2076 2077 2078 2079 2080 2081 2082 2083 2084 2085 2086 2087 2088 2089 2090 2091 2092 2093 2094 2095 2096 2097 2098 2099 2100 2101 2102 2103 2104 2105 2106 2107 2108 2109 2110 2111 2112 2113 2114 2115 2116 2117 2118 2119 2120 2121 2122 2123 2124 2125 2126 2127 2128 2129 2130 2131 2132 2133 2134 2135 2136 2137 2138 2139 2140 2141 2142 2143 2144 2145 2146 2147 2148 2149 2150 2151 2152 2153 2154 2155 2156 2157 2158 2159 2160 2161 2162 2163 2164 2165 2166 2167 2168 2169 2170 2171 2172 2173 2174 2175 2176 2177 2178 2179 2180 2181 2182 2183 2184 2185 2186 2187 2188 2189 2190 2191 2192 2193 2194 2195 2196 2197 2198 2199 2200 2201 2202 2203 2204 2205 2206 2207 2208 2209 2210 2211 2212 2213 2214 2215 2216 2217 2218 2219 2220 2221 2222 2223 2224 2225 2226 2227 2228 2229 2230 2231 2232 2233 2234 2235 2236 2237 2238 2239 2240 2241 2242 2243 2244 2245 2246 2247 2248 2249 2250 2251 2252 2253 2254 2255 2256 2257 2258 2259 2260 2261 2262 2263 2264 2265 2266 2267 2268 2269 2270 2271 2272 2273 2274 2275 2276 2277 2278 2279 2280 2281 2282 2283 2284 2285 2286 2287 2288 2289 2290 2291 2292 2293 2294 2295 2296 2297 2298 2299 2300 2301 2302 2303 2304 2305 2306 2307 2308 2309 2310 2311 2312 2313 2314 2315 2316 2317 2318 2319 2320 2321 2322 2323 2324 2325 2326 2327 2328 2329 2330 2331 2332 2333 2334 2335 2336 2337 2338 2339 2340 2341 2342 2343 2344 2345 2346 2347 2348 2349 2350 2351 2352 2353 2354 2355 2356 2357 2358 2359 2360 2361 2362 2363 2364 2365 2366 2367 2368 2369 2370 2371 2372 2373 2374 2375 2376 2377 2378 2379 2380 2381 2382 2383 2384 2385 2386 2387 2388 2389 2390 2391 2392 2393 2394 2395 2396 2397 2398 2399 2400 2401 2402 2403 2404 2405 2406 2407 2408 2409 2410 2411 2412 2413 2414 2415 2416 2417 2418 2419 2420 2421 2422 2423 2424 2425 2426 2427 2428 2429 2430 2431 2432 2433 2434 2435 2436 2437 2438 2439 2440 2441 2442 2443 2444 2445 2446 2447 2448 2449 2450 2451 2452 2453 2454 2455 2456 2457 2458 2459 2460 2461 2462 2463 2464 2465 2466 2467 2468 2469 2470 2471 2472 2473 2474 2475 2476 2477 2478 2479 2480 2481 2482 2483 2484 2485 2486 2487 2488 2489 2490 2491 2492 2493 2494 2495 2496 2497 2498 2499 2500 2501 2502 2503 2504 2505 2506 2507 2508 2509 2510 2511 2512 2513 2514 2515 2516 2517 2518 2519 2520 2521 2522 2523 2524 2525 2526 2527 2528 2529 2530 2531 2532 2533 2534 2535 2536 2537 2538 2539 2540 2541 2542 2543 2544 2545 2546 2547 2548 2549 2550 2551 2552 2553 2554 2555 2556 2557 2558 2559 2560 2561 2562 2563 2564 2565 2566 2567 2568 2569 2570 2571 2572 2573 2574 2575 2576 2577 2578 2579 2580 2581 2582 2583 2584 2585 2586 2587 2588 2589 2590 2591 2592 2593 2594 2595 2596 2597 2598 2599 2600 2601 2602 2603 2604 2605 2606 2607 2608 2609 2610 2611 2612 2613 2614 2615 2616 2617 2618 2619 2620 2621 2622 2623 2624 2625 2626 2627 2628 2629 2630 2631 2632 2633 2634 2635 2636 2637 2638 2639 2640 2641 2642 2643 2644 2645 2646 2647 2648 2649 2650 2651 2652 2653 2654 2655 2656 2657 2658 2659 2660 2661 2662 2663 2664 2665 2666 2667 2668 2669 2670 2

Trakus, Inc. of Medford, MA, in their Internet site <http://www.Trakus.com>, describe an RF system which converts object motion into digital data that can be analyzed or used for entertainment purposes. Their product, designed for hockey and football, provides information about an athlete's movements on the playing field.
5 Each athlete wears a transmitter which weighs two ounces. The transmitters send signals to antennas that surround the playing field. The system operates in spread spectrum because of the presence of other RF signals at base frequency of 2.45 GHz. The system uses time of arrival (TOA) measurements to calculate a player's position on the field. Sample rate of these measurements is about 30 times per second for each
10 player on the field.

Providing a method and apparatus for real-time measurement of human body motion has been a continuing problem for clinical researchers, athletic coaches and live-sports commentators, to name a few. There is a great emphasis on knowing the outcome of medical treatment and extraordinary interest in using such motion
15 information to enhance competitive athletics and to complement sports, industry, the military and entertainment. The inability of currently-used technology, to provide inexpensive, real-time analysis of the motion of limbs and joints has been frustrating. This is particularly true of widely used optical systems. Relatively new radio frequency approaches have not yet been applied to the detailed measurements required
20 for the applications mentioned above. Producing analytical measurement of human motion, at a high sampling rate and with high resolution will revolutionize the field of human performance analysis, among other things, by expanding the range of application and reducing the cost of necessary healthcare for disabled persons. Solving these problems would constitute a major technological advance and would
25 satisfy a long felt need in medicine, athletics, and recreation and entertainment industries.

SUMMARY OF THE INVENTION

5 An objective of the present invention is to develop a precision position measurement system that uses radio frequency (RF) phase interferometry. Energy sources, which are transmitting antennas disposed on a subject, are continuously located by receiving apparatus to a resolution of one millimeter (mm). This data is used, for example, in clinical gait analysis applications. Advantages include significant time savings for data analysis, real-time motion acquisition and display, high frame-rate acquisition, full body motion acquisition and reduced data loss from occlusion of markers on the subject. Enhancement of human body motion performance is an end result. Two methods of measuring position are contemplated.

10 The first measurement method uses a single antenna at each of several widely separated receiving locations to "triangulate" each energy source. By examining the differences in signal phase at pairs of receiving locations, source position is determined by one of two approaches. A first approach uses a known starting position for a source and computes changes in position. A second approach computes position by examining the enclosed volume for physical positions where the measured phase relationship would occur.

15 The second measurement method uses a small array of antennas at each of several receiving locations. Each array is able to determine the direction of arrival of the transmitted signal and the transmitter location is determined from the intersection of the direction-of-arrival vectors.

20 While the discussion which follows focuses on human body motion as an example, the measurement techniques of this invention can also be applied to animals, robotics, mechanical metrology and other articulated bodies and machines.

25 The *Body Motion Tracking System* measures path lengths to a number of receiving antennas from a source or "marker" antenna, disposed on a subject at a physical location to be tracked, to provide an estimate of the source's position time history.

Four to six receiving antennas are positioned at the edges of a volume in which activity is being conducted. Each antenna is coupled to a preamplifier which drives a mixer. In a preferred embodiment, the received signal is down-converted to translate the RF energy from microwave frequency to an intermediate frequency (IF) of about three Megahertz (MHz). A single reference oscillator must be fed to all of the mixers in order to preserve the phase relationships of the RF signals from the receiving antennas. The IF signals are presented to a bank of analog-to-digital converters which transform the analog signals to a digital signal format. A common sampling clock, operating in one embodiment at sixteen MHz, is used in this conversion process. Choice of clock frequency depends on the hardware selected and whether direct or sub-sampling is desired. The use of a common clock is required to preserve the phase relationships of the RF signals received.

Digital representations of the received signals are presented to the inputs of a multi-channel digital tuner. The digital signals are translated again to about one KHz. Narrow-band filtering and sampling rate reduction are applied. Phase relationships are still preserved because all of the signal processing up to this step is "coherent."

The digital data is fed to a main computer and processed to estimate each marker antenna's position. There are significant differences between this technique and conventional direction finding techniques.

Conventional DF systems consist of a number of small arrays of receiving antennas. They operate with the assumption that the range from a source to a receiving antenna is very large relative to the spacing of the antennas in the receiving array. As a result, the RF energy wavefront can be represented as a "plane wave" at the receiving array. In conventional DF systems, each receiving location measures the "angle of arrival" of the RF energy with respect to a system reference direction by phase measurement at adjacent pairs of antennas. The position of the source is estimated by "triangulation," that is, finding the intersection of lines drawn from each of three or more receiving locations, along the angle of arrival measured at that location.

5 The present invention employs differential phase measurement between pairs of widely spaced antennas to determine source position. The range (distance) from a transmitter (source) to a receiver uniquely determines the phase difference between the transmitted and the received signals. The difference in the ranges from a transmitter to two receivers uniquely determines the phase difference in the two received signals. The locus of points with the same range difference is one-half of a hyperbola of revolution with the two receivers as foci. Thus, barring abnormal placement of the receive antennas, the range difference for three pairs of antennas (four antennas total) determines a unique transmitter position within a workspace.

10 In one preferred embodiment of the present invention, the source transmits a continuous wave (CW) signal, i.e., a sine-wave. All range differences that differ by an integer number of wavelengths for a pair of receiving antennas, produce the same value of phase difference. Therefore, the locus of points having the same phase difference at a pair of receiving antennas is a family of hyperbolas of revolution having the two antennas as foci. Adjacent hyperbolas are one-half wavelength apart where they intersect the line joining the two antennas. Phase difference measurements using several pairs of receiving antennas may produce many equally valid solutions for transmitter position. However, if the volume of space containing the correct solution is suitably constrained, the phase difference measurements will produce only one valid solution.

20 Changes in the transmitter position will alter the lengths of the signal paths and therefore the phases of the received signals. However, if an estimate of the position of a transmitter is available and the next set of phase difference measurements is made when the transmitter could not have moved more than a small fraction of wavelength, then the volume in which the new transmitter position must be found is small enough to contain only one solution to the phase-difference equations and the new position can be determined uniquely. Because of the physics of RF propagation in a linear, isotropic medium, changes in phase difference measurements from time-to-time are due to transmitter movement.

5 The present invention contemplates several methods of establishing an initial position of the transmitter antenna. Each method may be appropriate for different applications of the invention. The simplest method requires the transmitter antenna to start from a particular position. A second method, using a small array of antennas at each receiving antenna location, allows calculation of a line-of-sight from each receiving antenna position to the transmitting antenna. As in conventional DF systems, the intersection of these lines-of-sight provide a position estimate sufficient to initialize phase difference tracking. A third method employs a large number of receiving antennas. When the number of such antennas is sufficiently large, a unique transmitter position can be determined, although the amount of computation increases dramatically with the number of receiving antennas.

10 The third method of establishing an initial position of the transmitting antenna requires finding its position in a large workspace with no information other than phase difference of received signals. The solution is found as follows: For each pair of receive antennas, the path length difference is an integer number of signal wavelengths plus a fractional part of a wavelength. The phase difference in the two received signals is a measure of the fractional wavelength part of the path length difference. The workspace geometry determines the range of possible integer values of path length difference. Each integer value defines a different hyperbola of revolution. By evaluating all possible combinations of integer values, one combination for each receiver pair, the point where all the hyperbolas intersect is found. This point then represents the initial position of the transmitting antenna.

15 Each signal enables identification and tracking of single energy source. In one preferred embodiment, a single unmodulated frequency is transmitted. The signal is switched between each of the marker antennas located on a subject of motion study in a known sequence. The signal is emitted from the marker antennas and the propagated signal is received by a plurality of receiving antennas. The receiving apparatus uses the known switching sequence to identify the transmitter associated with each emitted signal and the uses the procedures described above to estimate the

position of each marker antenna.

In another embodiment, each marker antenna transmits the same carrier frequency modulated with a different orthogonal signature waveform or code sequence. The receiving apparatus uses the orthogonality of these signature codes to
5 separate the signals from each marker antenna. The receiving apparatus then uses the procedures described above to estimate the position of each marker antenna. Because the orthogonality of the code sequences allows the receiving apparatus to separate the signals from the marker antennas, all marker antennas can transmit all the time. Continuous tracking of each one of the marker antennas is thereby enabled. This
10 technique supports use of spread spectrum transmissions. The two preceding embodiments can be used in combination, each signature code being time-multiplexed between several marker antennas.

An appreciation of other aims and objectives of the present invention may be achieved by studying the following description of preferred and alternate
15 embodiments and by referring to the accompanying drawings.

A BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is schematic diagram of an application of the present invention. It depicts a person who moves in a volume of space and on whom transmitting antennas are placed whose signals are tracked by receiving antennas. The receiving antennas deliver signal phase information to a computer for calculation of the persons body motion.

Figure 2 is a photograph of a child on whom transmitting antennas are disposed.

Figure 3 is a computer presentation of position and motion of the transmitting antennas depicted in Figure 2, describing the child's body motion as seen from the side.

Figure 4 is a computer presentation of the body position and motion shown in Figure 3, as seen from a front quarter.

Figure 4a is a chart of *Body Motion Tracking System* accuracy versus processing time showing regions of desired accuracy and processing time for four categories of applications of the present invention.

Figure 5 reveals a block diagram of the radio frequency apparatus used in the present invention to track and measure human body movement.

Figure 6 is a schematic diagram describing the prior art of direction finding by "triangulation" as a method for estimating the position of a source of radio frequency energy.

Figure 6a is a further diagram describing prior art of direction finding which depends on the assumption that an RF source lies at an angle to the receiving antenna boresight line and the received wave front is planar.

Figure 7 depicts a schematic diagram of a method used in the present invention

to measure by phase differences the relative position and motion of a source of radio frequency energy at widely separated antennas.

Figure 8 presents a schematic diagram illustrating a method used in the present invention to estimate the position of an RF energy source using best-fit phase differences at a number of receiving antennas.

5

TER2000-1

A DETAILED DESCRIPTION OF PREFERRED & ALTERNATIVE EMBODIMENTS

Motion Capture

Figure 1 is a schematic diagram of an application of the present invention which illustrates its features for capturing the position and movement of a subject body. The drawing depicts a subject person 12 who moves in a volume 16 of space and on whom "marker" antennas 14 are placed whose signals are tracked by receiving antennas 18. Each marker antenna 14 is a source of radiant energy. The receiving antennas 18 are dispersed and describe the boundaries of the volume 16. The receiving antennas 18 and their respective receiver apparatus deliver signal phase information to a computer for calculation of the person's body motion.

A low-power transmitting apparatus is disposed on the subject person 12. The transmitting apparatus supplies RF signal energy 40 to the marker antennas 14. In one preferred embodiment, each marker antenna 14 is separately selected and excited by a conventional switching matrix. The receiving system 42-51 can synchronize itself with the switching sequence because the switching sequence is known in advance. Thus, the receiving system 42-51 always knows which marker antenna 14 is transmitting. The output data of the receiving system 42-51 consists of an marker antenna code and its sequence of positions in volume 16.

Figure 2 is a photograph of a child 30 on whose lower extremities a plurality of marker antennas 14 are disposed. Over twelve million people in the United States have lower extremity disabilities, according to the U.S. Dept. of Health and Human Services (1994). Five hundred thousand Americans have cerebral palsy, growing at the rate of 4,500 cases per year. Extension of these statistics to the entire world population indicates how serious is solving the problem of saving time and money if

a substantial percentage of these cases is to be treated. Clinical gait analysis is a diagnostic tool for prescribing treatment for those patients who suffer with neuromuscular, musculoskeletal, or neurological impairments. The primary goal in treating a person who has these problems is to correct their functional deficiencies and thereby improve their quality of life. Functional deficiencies are quantified analytically by having the subject perform simple tasks while patterns of limb movements are systematically measured. Motion-capture data reduces the number of surgeries required to correct some problems.

Figure 3 is a computer presentation of position and motion of the marker antennas depicted in Figure 2, describing the child's body motion as seen from the side. Figure 4 is a computer presentation of the body position and motion as shown in Figure 3, but seen from a front quarter. It is obvious that the body motion of the child 30 can be viewed on the computer screen in real time both qualitatively and quantitatively. Of course, the data can be save for later referral and comparisons.

Requirements for measurement accuracy, processing time, work-space volume and cost for clinical gait analysis, capabilities of existing devices and capabilities of the present invention are shown in Table 1 below.

Table 1. Requirements vs. Capabilities for *Body Motion Tracking System*

	Accuracy	Processing Time	Work-Space Volume	Cost
Requirements	< 1 millimeter	Real Time	Large	Low
Existing Devices	1 to 2 millimeters	Three frames latency	1 x 2 x 1.5 meters	≈ \$200,000.
<i>Body Motion Tracking</i> Capabilities	1 to 2 millimeters	Real Time	10 x 10 x 3 meters	≈ \$50,000.

Besides the direct savings shown above, real-time motion capture reduces the clinical manpower required by about 30 %. A large volume in which to work reduces the number of motion-capture data runs, an additional savings of time and manpower.

Figure 4a is a chart which displays envelopes of requirements for accuracy 20 versus processing time 22 for clinical applications 24 and other applications 23, 25, 26 for the *Body Motion Tracking System*. Clinical applications 24 are the most demanding for accuracy 20 and processing time 22. Performance improvement applications 23 such as competitive sports and military equipment evaluation, industrial applications 25 and animation 26 in films and television entertainment will clearly benefit from the high accuracy 20 and low processing time 22 of the *Body Motion Tracking System*.

A block diagram of the *Body Motion Tracking System* apparatus is revealed in Figure 5. An RF transmitter 30 drives a plurality of marker antennas 14. Radiated energy signals 40 from the marker antennas 14 are received by a plurality of receiving antennas 18. The radiated signal 40 from a given marker antenna 14 is received by the receiving antennas 18 which are widely separated, at slightly different times because of the different path lengths from the marker antenna 14 to the different receiving antennas 18. The time differential is reflected as a phase difference in the received signal at each receiving antenna 18.

A minimum of four, preferably more, receiving antennas 18 are positioned at the edges of the volume 16 in which the subject body's activity is being conducted. The number of receiving antennas 18 is chosen so that an optimum set can be switched or selected. For each measurement interval, the signals from four to six of the receive antennas are used to estimate marker antenna 14 positions with receive antennas selected by a figure of merit. The figure of merit is ordinarily based on errors, data noise and prediction of clear radiation paths away from the body. Each received signal 40 is boosted in a preamplifier 42 and then down-converted in one of a plurality of mixers 44.

In one preferred embodiment, the RF energy is translated from a microwave frequency of about 2.5 GHz. to an intermediate frequency (IF) of about three Megahertz (MHz). A single reference oscillator 46 is fed to all of the mixers 44 in order to preserve the phase relationships of the RF signals from the receiving antennas 18. Each IF signal is presented to one of a bank of analog-to-digital converters 48 which transform the analog signals 40 to a digital signal format. A common sampling clock, operating in one embodiment at sixteen MHz, is used in this conversion process. Choice of clock frequency depends on the hardware selected and whether direct or sub-sampling is desired. The use of a common clock also preserves the phase relationships of the RF signals 40 received. Digital representations 49 of the received signals are presented to the inputs of a multi-channel digital tuner 50. The digital signals 49 are translated again to about one KHz. Narrow-band filtering and sampling rate reduction are applied. Phase relationships are preserved because all of the signal processing up to this step is "coherent."

The digital data 49 is fed 51 to a main computer and processed to estimate the marker antenna's position relative to each receiving antenna 18. This process is related to conventional direction finding (DF) techniques, but there are significant differences between the present invention and conventional DF. Figures 6 and 6a help to understand the conventional DF technique.

Conventional Direction Finding Systems

Conventional DF systems such as shown in Figure 6, and 6a operate with the assumption that the range 63, 65, 67 from each of the receiving locations 62, 64, 66 to the source antenna 61 is very large relative to the spacing of receiving antenna elements 62a, 62b. Therefore, RF energy wavefront 68 can be represented as a "plane wave" 68a. Each receiving location 62, 64, 66 comprises antenna element pairs 62a, 62b which form simple interferometers. It is also assumed that the RF source 61 is located to one side of the receiving antenna array. In DF techniques, the receiving locations 62, 64, 66 "triangulate" the source 61. In a simple DF system, each

receiving location 62, 64, 66 measures the direction to the energy source or “angle of arrival” $\theta_1, \theta_2, \theta_3$ by phase measurement at pairs of closely spaced antennas 62a, 62b. Position of the source is estimated by finding the intersection of lines drawn from each receiving location 62, 64, 66 along the angle of arrival $\theta_1, \theta_2, \theta_3$.
5 Because of unavoidable measurement errors, these lines will not all intersect at the same point and the source position 61 is estimated by finding a single point that is closest to all of the lines.

In Figure 6a, the angle of arrival θ_1 is determined by the phase difference between the two receiving antenna elements 62a, 62b. When the source 61 is offset from the antenna boresight line 69, the propagated RF wave front 68a reaches the two antenna elements 62a, 62b at different times. The differential path length δ from the source 61 to the second antenna element 62b and the signal wavelength λ produce the phase difference $\Delta\phi$ at the second antenna element 62b with relation to the first antenna element 62a. If the differential path length δ is less than one wavelength, the phase difference $\Delta\phi$ is given by equation one.
10
15

$$\Delta\phi = 2\pi * \delta / \lambda \quad \text{Equation 1.}$$

Simple trigonometry relates the differential path length δ , the distance between the antenna elements and the angle of arrival θ_1 . This triangulation technique using at least three receivers has substantial inaccuracies in small work volumes and where the signal source 61 lies close to the receiving antennas 62a, b.
20

Finding Relative Position by Differential Phase Measurement
Using Single Antennas

The present invention employs differential phase measurement at a plurality of single antennas widely spaced one from the other. Figure 7 illustrates one preferred embodiment of this technique.

When the energy source 73 is at a starting position 72, the lengths along the paths 80, 84 determine the phase of the propagated signal 60 at a first receive antenna 76 and at a second receive antenna 78. The difference in these phase measurements, $\Delta\phi_1$, is given by Equation 2:

$$\Delta\phi_1 = (2\pi (d_{12} - d_{11}) / \lambda) \text{ modulo } 2\pi \quad \text{Equation 2.}$$

where d_{11} is the distance along the path length 80 from the first receive antenna 76 to the energy source 73 at its starting position 72 and d_{12} is the distance from the second receive antenna 78 to the energy source 73 at its starting position 72.

If the energy source 73 moves from its starting position 72 to a second position 74, the new path lengths 88, 86 determine a new phase measurement at the first receive antenna 76 and at the second receive antenna 78. The new phase difference measurement, $\Delta\phi_2$, is given by Equation 3:

$$\Delta\phi_2 = (2\pi (d_{22} - d_{21}) / \lambda) \text{ modulo } 2\pi \quad \text{Equation 3.}$$

where d_{21} is the distance along the new path 88 from the first receive antenna 76 to the energy source 73 at its second position 74 and d_{22} is the distance from the second receive antenna 78 to the energy source 73 at its second position 74.

The change in relative phase of the received propagated signal 60 is dependent only on the wavelength λ of the signal 60 and the distance moved 82 by the energy source 73. This system *does not require* the use of an absolute phase reference.

If the distance moved 82 is small, the change in path length difference is Δd and is given by Equation 4:

$$\Delta d = (d_{22} - d_{21}) - (d_{12} - d_{11}) = \lambda (\Delta \phi_2 - \Delta \phi_1) / 2\pi \quad \text{Equation 4.}$$

If one assumes the path 84 from the second receive antenna 78 to the energy source 73 remains a constant length d_{12} , then the energy source 73 at its second position 93, would be at the intersection of arc 91 and arc 92. On the other hand, if one assumes the path 80 from the first receive antenna 76 to the energy source 73 remains a constant length d_{11} , then the energy source 73 at its second position 96, would be at the intersection of arc 94 and arc 95. If the actual position of the energy source 73 is at the second position 74, then the source 73 will lie on a line 97 drawn through the two points of arc intersection 93 and 96.

Considering the energy source 73 to move in the same plane as that containing the first receive antenna 76 and the second receive antenna 78, a third receive antenna, paired with one of the other two receive antennas 76, 78 would construct a third path to the energy source 73 at its second position 74. The intersection of the first path 88, second path 86 and third path will unambiguously locate the energy source 73.

Consider now a three-dimensional case in which the energy source 73 at its second position 74 does not necessarily lie in the plane defined by the receive antenna locations 76,78 and the energy source 73 at its first position 72. In this case, the second position 74 will lie on a surface, and the line 97 is the intersection of this surface with the plane defined by the receive antenna locations 76,78 and the first position 72. To unambiguously locate the energy source 73 on this surface, two additional receive antennas are required, a total of four receive antennas. Using three different pairs of receive antennas, three such surfaces will be constructed. The position of the energy source 73 will be at the intersection of these three surfaces.

If the absolute starting position 72 of the energy source 73 is known, the new absolute position 74 is then calculated. This procedure is continued for each energy source 73 disposed on a subject body for the duration of the motion-capture process. As already indicated above, the position data is displayed in real time but can be saved for further review and analysis.

Because the change in phase difference ($\Delta\phi_2 - \Delta\phi_1$) can be measured very accurately, the distance moved 82 by the energy source 73 can be measured to small fractions of a wavelength λ . For a source transmitting at a frequency of 2.45 GHZ, the wavelength λ is approximately 12 cm.

5 Absolute Position Determination Using Phase Differences and Redundancy

10 An alternative method of finding the absolute position of an energy source within a given volume uses a best-fit phase difference measurement. This method 100 is illustrated in Figure 8 for two receiving antennas 108, 110 and one energy source 102. The distance d between the transmitter source 102 and a receiver 108, 110 can be represented by an integer number n of wavelengths λ plus a fraction δ of one wavelength as shown in Equation 5.

$$d = n\lambda + \delta \quad \text{Equation 5.}$$

15 Because the transmitted signal is sinusoidal, the measured phase difference is equal to the total phase difference modulo 2π . This is mathematically shown in Equation 6.

When $|\delta_2 - \delta_1|$ is less than one wavelength λ :

$$\begin{aligned} \text{measured phase difference} &= (2\pi/\lambda) (d_2 - d_1) \text{ modulo } 2\pi && \text{Equation 6.} \\ &= (2\pi/\lambda) (n_2\lambda + \delta_2 - n_1\lambda - \delta_1) \text{ modulo } 2\pi \\ &= (2\pi/\lambda) (\delta_2 - \delta_1) \end{aligned}$$

20 Thus, all integer values of n_1 and n_2 give the same measured phase difference. Each pair of values of n_1 and n_2 defines a different hyperbola of revolution 112, the two receiving antennas 108, 110 being the foci. For each pair of receiving antennas 108, 110, the allowable values of $n_2 - n_1$ for a source within the measurement volume are:

$$\Delta n = n_2 - n_1 = 0, \pm 1, \pm 2, \dots, \pm N \quad \text{Equation 7.}$$

Where N is the number of half-wavelengths between the two receiving antennas 108, 110. The source 102 position is found by choosing a value of Δn for each pair of receiving antennas 108, 110 such that all of the surfaces of revolution 112 intersect at the same point, that being the source 102 position. For two pairs of receiving antennas 108, 110 (three antennas in all) there are many points of intersection. As more receiving antennas 108, 110 are added to the receiving system, the number of ambiguous solutions is reduced until only one, correct solution remains.

The solution is implemented by evaluating all allowable values of Δn for each antenna pair 108, 110 and selecting the set of values of Δn for which all the surfaces of revolution 112 intersect at the same point 102. This technique has been validated by simulation.

If the source position is known to be in a suitably small region, then all of the ambiguous solutions are outside of this region even for a minimum number of receiving antennas 108, 110 needed to locate the source 102 in three dimensions. That number is ordinarily four. Only one solution, the true one, is found inside the workspace volume searched. The conditions are satisfied if (1) the approximate source 102 starting position is known; or (2) the source 102 position has been estimated a short time earlier and the current position is limited by the maximum speed the source 102 is able to travel. This technique has been evaluated also in simulation.

In order to extend the work-space volume, additional banks of receiving antennas can be switched into use as the subject moves into their area of coverage. Such bank-switching antennas are useful in studying body motion of racers in a 50-yard dash, for example.

Tracking Multiple Energy Sources

Referring again to Figure 5, a propagated signal 40 enables identification and tracking of individual energy sources 14. In one preferred embodiment, a single unmodulated frequency is transmitted. The propagated signal 40 is switched between each of the marker antennas 14 located on a subject 12 of motion study in a known sequence, and it is received by a plurality of receiving antennas 18. The receiving apparatus 42-51 uses a known switching sequence to identify the marker antenna 14 associated with each data interval. The collection of data intervals from a single marker antenna are processed as described for the case of a single marker.

In another embodiment, each marker antenna 14 transmits the same carrier frequency modulated with a different orthogonal signature waveform or code sequence. The receiving apparatus 42-51 uses the orthogonality of these signature codes to separate the signals from each marker antenna 14. The receiving apparatus 42-51 then uses the procedures described above to estimate the position of each marker antenna 14. Because the orthogonality of the code sequences allows the receiving apparatus to separate the signals from the marker antennas, all marker antennas can transmit all the time. Continuous tracking of each one of the marker antennas 14 is thereby enabled. This technique supports use of spread spectrum transmissions.

The two preceding embodiments can be used in combination, each signature code being time-multiplexed between several marker antennas 14.

Alternate Embodiments

The discussion to this point has been directed principally to human body motion and in particular to clinical gait analysis in order to understand the concepts and certain embodiments of the present invention. Perhaps an even larger area of application is that of performance improvement. This includes motion studies for athletes and their coaches, evaluations of military personal equipment, combat training and virtual representation of real-life scenarios. Animation in computer games and presentations, industrial uses for measuring human-machine interfaces and machines (such as manufacturing robots) alone can profit from real-time, high-accuracy, low-cost motion studies.

CONCLUSION

Although the present invention has been described in detail with reference to particular preferred and alternative embodiments, persons possessing ordinary skill in the art to which this invention pertains will appreciate that various modifications and enhancements may be made without departing from the spirit and scope of the Claims that follow. The various hardware and software configurations that have been disclosed above are intended to educate the reader about preferred and alternative embodiments, and are not intended to constrain the limits of the invention or the scope of the Claims. The List of Reference Characters which follows is intended to provide the reader with a convenient means of identifying elements of the invention in the Specification and Drawings. This list is not intended to delineate or narrow the scope of the Claims.

LIST OF REFERENCE CHARACTERS

Figure 1

- 10 Body motion marker and receiving antennas
- 12 Subject of motion study
- 14 Marker antenna
- 16 Volume of space in which the subject moves
- 18 Receiving antenna

Figure 2

- 14 Marker antenna
- 30 Child subject of motion study

Figure 4a

- 20 Accuracy scale
- 22 Processing Time scale
- 23 Performance improvement applications envelope
- 24 Clinical applications envelope
- 25 Industrial applications envelope
- 26 Animation applications envelope

Figure 5

- 14 Marker antenna
- 18 Receiving antenna
- 30 Low-power RF transmitter
- 40 Propagated RF signal from marker antenna
- 42 Receiver pre-amplifier
- 44 RF Mixer
- 46 Reference oscillator

- 48 Analog-to-digital (ADC) converter
- 49 Digitized IF signal
- 50 Multi-channel digital tuner
- 51 Data feed to data processor

Figures 6 & 6a

- 40 Propagated signal
- 60 Prior art system of position-finding triangulation using angle of arrival (AOA) information
- 61 RF energy source
- 62 Receiving antenna array
- 62a Receiving antenna first element
- 62b Receiving antenna second element
- 63 Direction to source from first antenna array
- 64 Second receiving antenna array
- 65 Direction to source from second antenna array
- 66 Third receiving antenna array
- 67 Direction to source from third antenna array
- 68 RF propagation wavefront
- 68a Assumed planar wavefront
- 69 Antenna boresight line
- 69a Antenna baseline
- θ_1 Angle of arrival at first receiving antenna array
- θ_2 Angle of arrival at second receiving antenna array
- θ_3 Angle of arrival at third receiving antenna array

Figure 7

- 70 Sketch of the method of measuring relative position and motion of an energy source
- 72 Energy source's first position
- 73 Energy source
- 74 Energy source's second position
- 76 First receive antenna
- 78 Second receive antenna
- 80 Path from source at first position to first receiving antenna
- 82 Path on which source moves from first to second position
- 84 Path from source at first position to second receiving antenna
- 86 Path from source at second position to second receiving antenna
- 88 Path from source at second position to first receiving antenna
- 91 Arc centered on second receive antenna having a radius of d_{12}
- 92 Arc centered on first receive antenna having a radius change determined by total phase change in signal received at first receive antenna
- 93 Source position assuming distance from source to second antenna remains constant
- 94 Arc centered on first receive antenna having a radius of d_{11}
- 95 Arc centered on second receive antenna having a radius change determined by total phase change in signal received at second receive antenna
- 96 Source position assuming distance from source to first antenna remains constant
- 97 Locus of possible new positions of the energy source measured by phase change at two receiving antennas
- Δd Change in path length (range) difference corresponding to measured phase change
- d_{11} Length of path from energy source at first position to first receive antenna
- d_{12} Length of path from energy source at first position to second receive antenna

- d_{21} Length of path from energy source at second position to first receive antenna
- d_{22} Length of path from energy source at second position to second receive antenna

Figure 8

- 100 Sketch of the method used in the present invention to estimate the position of an RF energy source using best-fit phase differences at a number of receiving antennas.
- 102 Energy source
- 103 Position of energy source
- 104 Distance from the energy source to a first receiving antenna (No. of signal wavelengths plus a fractional signal wavelength)
- 106 Distance from the energy source to a second receiving antenna (No. of signal wavelengths plus a fractional signal wavelength)
- 108 First receiving antenna
- 110 Second receiving antenna
- 112 Lines of equal measured phase difference
- d_1 Distance from energy source to first receive antenna
- d_2 Distance from energy source to second receive antenna
- λ Transmitter signal wavelength
- n_1 Integer number of wavelengths from source to first receive antenna
- n_2 Integer number of wavelengths from source to second receive antenna
- δ_1 Fractional wavelengths from source to first receive antenna
- δ_2 Fractional wavelengths from source to second receive antenna